



OPTICAL WIRELESS LINK

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Technical Field of the Invention

This invention relates to optical data communication, and more particularly relates to systems for high bandwidth, optical, fiberless, path-to-sight data communications.

Background of the Invention

Low cost, high bandwidth, wireless data communication is an urgent goal in a number of areas of application. Local area networks (LANs) require high bandwidth data communication, as do infrastructure data communications systems, such as telephony and video systems, including internet applications. However, the time and expense of installing physical cabling or fiber between network or device nodes in many cases prohibits the practical installation or upgrading of systems. Other application areas could emerge, once a low-cost high bandwidth data link is available.

RF Wireless communication links have been utilized in the prior art. However, such links share bandwidth across multiple users in an area, provide access to the RF signal by all users resulting in security concerns, are subject to FCC regulations, and are practically limited to effective bandwidths per user which are much less than that of typical cabling and fiber optics. Open air, optical links have been utilized for data communications in the prior art. However, such links have typically suffered from high cost. One example of such a link uses a galvanometer type actuator for rotational control of an optical system. The optical system in such systems is typically a high precision lens structure

mounted on a large, precision mechanical assembly. The resulting system is high performance and high quality, but bulky, expensive and difficult to install, making it impractical for widespread use.

Summary of the Invention

In accordance with the present invention there is provided an optical, path-to-sight modem. The modem includes a controllable beam steering device, such as, for example, a micro-mirror, or any other device that changes the direction of the light beam without changing the orientation of the light emitter and includes an actuator to permit steering the light beam, the beam steering device being controllable by predetermined control signals. The modem includes a source of electronic data signals, and a source of light having a narrow beam of light controllable by the beam steering device. Means are provided for converting the electronic data signals to optical signals modulating the beam of light. Means are also provided for controlling the beam steering device so as to maintain the beam aligned to a receiver.

As used herein, the term path-to-sight is intended to mean an unobstructed optical path generally through the ether, as contrasted with through an optic fiber, which path can include reflections.

These and other features of the invention will be apparent to those skilled in the art from the following detailed description of the invention, taken together with the accompanying drawings.

Brief Description of the Drawings

Figure 1 is a block diagram of an optical wireless modem according to a preferred embodiment of the present invention;

Figure 2a is a side view of the transmitter section of the an optical module 228 of Figure 1,

Figure 2b is a side view of the receiver section of the optical module;

Figure 3 is a plan view of a mirror assembly used in the Figure 2a transmitter section;

Figure 3a is a cross sectional view taken on line 3a-3a of Figure 3;

Figure 3b is a view similar to Figure 3a but showing rotation of the mirror portion of the mirror assembly;

Figure 3c is a cross sectional view taken on line 3c-3c of Figure 3;

Figure 3d is a view similar to Figure 3c but showing rotations of the gimbal portion of the mirror assembly;

Figure 4 is an enlarged cross sectional plan view taken on line 4-4 of 3a showing a hinge and an in-plane motion stop;

Figure 5 is an enlarged, broken away portion of Figure 4 showing a portion of the in-plane stop;

Figure 6 is a cross sectional plan view taken on line 4-4 of Figure 3a showing a hinge with an optional lock down tab to stop rotation used during manufacture;

Figure 6a is a view similar to Figure 6 showing the lock down tab severed to allow rotation;

Figure 7 is a top plan view of an optical switch package made in accordance with the invention;

Figure 7a is a cross sectional view taken on line 7a-7a of Figure 7;

Figure 7b is a view similar to Figure 7 showing rotation of the mirror portion of the mirror assembly;

Figure 7c is a cross sectional view taken on line 7c-7c of Figure 7;

Figure 7d is a view similar to Figure 7c but showing rotation of the gimbal portion of the mirror assembly;

Figure 8 is an exploded view of a cross sectional, broken away portion of the bottom wall of the housing of an optical switching unit package and the mounting bracket;

Figure 9 is a top plan view of a modified embodiment of an optical switch unit with certain parts removed for purposes of illustration;

Figure **9a** is a cross sectional view of the top portion of an optical switch unit taken on line **9a-9a** of Figure **9**;

Figure **9b** is a view similar to Figure **9a** but showing rotation of the mirror portion of the modified mirror assembly;

Figure **10** illustrates the alignment of the optical transmitter with an optical receiver at a remote site;

Figure **11** is a flow chart in which the micromirror is controlled to scan the light beam in a circular spiral path.

Figure **12** is a schematic diagram of a second embodiment of the invention; and

Figure **13** is a schematic diagram of a third embodiment of the invention.

Detailed Description of the Preferred Embodiment

Figure 1 is a block diagram of an Optical Wireless Link ("OWL") **210** used in the preferred embodiment of the present invention. A Data Medium **212**, such as a data channel, network, device, or the like providing a source/sink of data is coupled by a two-way Data Link **214** to an Interface Unit **216**. The data transmitted to/from the Data Medium **212** may be either analog or digital data. Digital data may be in either parallel or serial format. Thus, the data can be analog or digital voice data, analog or digital video data, or any other form of data represented in electronic signal format.

The Interface Unit **216** performs conventional and necessary conversion and conditioning of the data to/from Data Medium **212**. This can take the form of dedicated hardware for conversion/conditioning of a specific data type, or it can be software configurable hardware that could handle multiple formats without interruption or delay as formats change. Or, it can take any of a number of intermediate forms. In all such embodiments, the purpose of Interface Unit **216** is as follows. If providing the function of receiving digital data, the purpose of Interface Unit **216** is to take such received digital data from an Encoder/Decoder **220**, described below, and convert such data to an format, analog or digital, suitable for transmission on Data Medium **212**, and to provide whatever conditioning of such signals is appropriate for the Data Medium **212**, converting such data to parallel format, if the Data Medium **212** requires parallel digital format. If providing the function of receiving analog data, the purpose of Interface Unit **216** is to take such received analog data signals, to provide whatever conditioning of such analog signals is appropriate for the Data Medium **212**, and provide them to the Data Medium **212**. The purpose of

Interface Unit **216** in the transmission of data is, if providing the function of transmission of analog data, to take analog signals and provide them appropriately to Encoder/Decoder **220**, or, if providing the function of transmission of digital data, to take serial or parallel digital data and provide such data appropriately to Encoder/Decoder **220**, converting such data to serial format if provided by Data Medium **212** in parallel format. The interface art is mature and well known, and the construction and operation of any such interface unit appropriate for the particular context to which the OWL **210** is applied is well within the purview of those skilled in this art.

The Interface Unit **216** is coupled by a two-way Data Link **218** to an Encoder/Decoder unit **220**. The Encoder/Decoder unit **220** is likewise of conventional construction and operation. It encodes serial data from Interface Unit **216** as needed for transmission and decodes received data for provision to Interface Unit **216**. Encoding may also include parceling the data in packets, adding Operation/Administration/Maintenance ("OAM") data from a link control DSP/Microcontroller **238**, described below, and/or adding error correction/detection information. Decoding may also include extracting the data from received packets, extracting OAM information for the link control DSP/Microcontroller **238**, and/or performing error correction/detection. The encoding/decoding art is mature and well known, and the construction and operation of any such encoding/decoding unit appropriate for the particular context to which the OWL **210** is applied is well within the purview of those skilled in this art. For example, encoder/decoders for the Ethernet protocol, asynchronous transfer mode ("ATM") protocol, SONET protocol, Token Ring protocol, etc., are all well known in the art, and may be used for Encoder/Decoder unit **220**, as the case may be.

An in-depth discussion of the general principles of implementation and operation for both the Interface Unit **216** and the Encoder/Decoder Unit **220** may be found in *Digital Modulation and Coding*, Stephen G. Wilson, Prentice Hall, Upper Saddle River, N.J., 1996. Specific principles of implementation and operation for such units in connection with the Ethernet protocol can be found in *Gigabit Ethernet Handbook*, Stephen Saunders, McGraw Hill, New York, NY, 1998. In addition, numerous off-the-shelf components are available for implementing these units. For example, again in the Ethernet context, Texas Instruments Incorporated offers the "10/100 Ethernet PHY" component, that may be used as the Interface Unit **216**. In addition, Texas Instruments Incorporated offers the "TNETE2201B, 1.25-Gigabit Ethernet Transceiver" component, that may be used as the Encoder/Decoder Unit **220**. Examples of encoding schemes include Ethernet, fiber channel and Asynchronous Transfer Mode, and IEEE 1394.

The Encoder/Decoder Unit **220** is coupled by a two-way Data Link **222** to an Optical Transceiver Unit ("OTU") **224**. The OTU **224** acts as an electrical to light and light to electrical converter. It contains a light source such as a laser or light emitting diode, control electronics for the light source, a photo-detector for converting the received light to electrical signals and amplifiers to boost the electrical signal strength to that compatible with the decoder.

The OTU **224** can also be of conventional design. For example, a TTC-2C13 available from TrueLight Corporation of Taiwan provides an advantageous and low cost optical transceiver unit, requiring only a single +5V power supply, consuming low power, and providing high bandwidth. However, it should be noted that OTU units of conventional design can provide less than optimal performance, since such units are typically designed for transmitting and receiving light from fibers. This results in

three problems that should be noted by the designer. First, light is contained in such units and is thus not subject to the same eye safety considerations as open air optical systems such as the present invention. Consequently, such units may have excessively high power. Second, light is transmitted to a fiber and thus has optical requirements that are different from those where collimation is required, as in embodiments of the present invention. Third, light is received by such units from a narrow fiber, and therefore such units usually have smaller detector areas than desired for embodiments of the present invention. Accordingly, it is considered preferable to assemble a transceiver having a photodiode and optical design such that the maximum amount of light is collected from a given field of view. This requires as large a photodiode as possible, with the upper limit being influenced by factors such as photodiode speed and cost. In any event source, a preferred light source is a vertical cavity surface emitting laser, sometimes referred to as a VCSEL laser diode. Such laser diodes have, advantageously, a substantially circular cross-section emission beam, a narrow emission cone and less dependence on temperature.

The Optical Transceiver Unit **224** is coupled by a two-way data link **226** to an Optical Module **228**. The Optical Module **228** contains optical components for collimating or focussing the outgoing light **254** from the transceiver, a micro-mirror controlled by, e.g., electromagnetic coils shown and described below, for directing the collimated light in the direction of a second OWL (not shown), with which OWL **210** is in communication, and receiving optics to concentrate the light received from the second OWL on a transceiver photodetector included in the Optical Module **228**. The receiving optics can include a control mirror, either flat or curved, to direct the light to the photodetector. Auxiliary photodetectors can be provided adjacent to the main photodetector for light detection in

connection with a control subsystem (not shown), for controlling the control mirror, and maximize the light capture at the photodetector. The Optical Module 228 may also contain a spectral filter 230 to filter ambient light from the incoming signal light 256. The Optical Module 228 is described in detail below. It should be understood, however, that the Optical Module 228 described herein is merely a preferred embodiment thereof, and that other variations are possible. For example, a micro-mirror need not be used, but rather any controllable beam steering device can be used that changes the direction of the light beam without changing the orientation of the light emitter. In addition, a basic function of the Optical Module 228 is that it sufficiently collimate the light into a beam that will (1) substantially fit within the micro-mirror reflecting area, and (2) preserve the minimum detectable optical power density over the distance of the link. Laser diodes generally meet these criteria, and as such are preferred. However, light emitting diodes ("LEDs") and other light sources can be made to satisfy these criteria, as well. Note that, as used herein, the term micro-mirror refers to a device including a rotatable mirror element, in which the mirror element has a mass no greater than eight grams.

For optical wireless links across large distances where the highest possible optical power density at the receiver is needed for robust transmission, the optical transmitter portion of this embodiment should preferably be selected to achieve a divergence of less than 0.5 mrad, which is to be contrasted with the prior art systems mentioned above that have divergences in the range of 2.5 mrad. The divergence of less than 0.5 mrad results in an optical density greater than 25 times the optical density of the prior art systems, which, for the same received optical power density corresponds to 5 or more times longer range.

The optical receiver portion of this embodiment should be selected to have an intermediate size, preferably having a diameter in the range of 0.5 millimeter (mm) to 1 centimeter (cm). If the diameter is much smaller than 0.5 mm, it may be difficult to collect enough of the light directed on the receiver. On the other hand, if the diameter is much larger than 1 cm, the responsiveness of the detector may diminish to the point where the performance of the system is compromised.

It should also be understood that more than one Optical Transceiver unit **224** may be provided in some embodiments, for example to provide multiple wavelengths to transmit information across a single link, in order to increase the bandwidth of a given OWL link. This involves generating light beams having multiple wavelengths and collecting and separating these separate light beams. Numerous apparatus and methods are known in the art to accomplish this.

The Optical Module **228** is coupled by an optical path **232** to a Position Sensitive Detector ("PSD") **234**. The PSD **234** measures the angular deflection of the micro-mirror in two planes by detecting the position of a spot of light on a sensor in the PSD **234**. The analog signals representing these angular deflections are converted into digital signals and sent on lines **236** to a Digital Signal Processor ("DSP") **238** for closed loop control of the micro-mirror in Optical Module **228**. PSDs are well known in the art, and PSD **234** may be any of a variety of types, including a single diode Si PSD, CMOS photo-detector array, and the like. All that is required of PSD **234** is that it sense, in two directions, the position of a spot of light impinging thereon, and provide as outputs digital signals representative of such position. However, note that the use of analog control signals is not required in the practice of the present invention. Other known control signal approaches can be used. For example, pulse width modulation may be used to provide such control. Such choices of

control system are well within the purview of those of ordinary skill in this art.

In addition to receiving the signal lines **236** from the PSD **234**, the DSP **238** sends coil control signals on lines **240** to a set of coil digital to analog converters ("D/As") **242**. The D/As **242** are, in turn, connected by way of lines **244** to a corresponding set of coils, shown and described in detail below, in Optical Module **228**. The DSP **238** is also connected to send data on a line **246** to, and receive data on a line **248** from a secondary Link **250**. Finally, the DSP **238** is connected via line **252** to send and receive OAM data to/from Encoder/Decoder **220**.

The DSP **238** operates as a link control. It controls the micro-mirror deflections by controlling the coil currents through the D/As **242**. Information on the instantaneous micro-mirror deflections is received from the PSD **234** for optional closed loop control. The DSP **238** also exchanges information across the Secondary Link **250** to the second OWL to orient the beam steering micro-mirror in the proper direction for the link to be established and maintained. The DSP **238** may also exchange OAM information with the second OWL across the optical link maintained by Optical Module **228**.

DSP **238** may be any suitable DSP, of which many are commercially available. Optionally, a microcontroller may be used in the place of DSP **238**. In addition, note that a single processor may control multiple OWL links. This capability can be very valuable for use in a network hub, where multiple links originate or terminate in a single physical network switch. A single DSP could provide a very cost efficient control facility in such cases. In all such cases, the requirements for this processor are a sufficiently high instruction processing rate in order to control the specified number of micro-mirrors, and a sufficient number of input/output ("I/O") ports to manage control subsystem devices and

peripheral functions. A suitable DSP for many such embodiments is a Texas Instruments Incorporated DSP from its C5x family of DSP microprocessors.

The Secondary Link **250** is used to transfer low bandwidth information between the OWLs. This information can be used to aid establishment of the optical link by transferring the strength of the received signal. The Secondary Link **250** is a low bandwidth link, and may be, for example, an RF link such as the Bluetooth link, or IR link such as the type used in remote controllers for electronic devices such as televisions, VCRs, hi-fi systems, and the like. The Secondary Link **250** could also be an existing physical link, such as a telephone line, power line, or other existing lower bandwidth network. Construction and operation of such links are well known in this art.

The Optical Module **228** will now be described. This unit is very compact, high speed in operation, low cost and reliable in operation. The optical module contains a transmitter section, shown in Figure **2(A)**, and a receiver section, shown in Figure **2(B)**. In the transmitter section, light emitted by the light source **501** in the optical transceiver unit is focused or collimated by lens **502** in an optical beam **503**. The optical beam **503** is reflected by a mirror in a rotatable mirror assembly **504**, the mirror being shown in its middle or neutral unpowered position, in direction **505**. The rotatable mirror is moveable between two opposite extremes, with optical beam **503** correspondingly reflected to **505'**, **505"** at the extremes. Although the movement of the mirror shown in Figure **2(A)** illustrates movement in one plane, mirror movement in a second plane is also included in the operation of the optical wireless link and will be described below. The reflected optical beam passes through a beam splitter **506** that reflects a portion of the beams **505**, **505'** and **505"** in directions **507**,

507' and **507"**, respectively, to the PSD **234** and transmits the rest of the beam out of the optical wireless link.

The receiver section of the optical module contains optics **510** for concentrating in incoming light **511** onto the photodiode **509** in the optical transceiver unit to increase the received optical signal. The optics can be imaging optics with the photodiode at the focal plane or non-imaging optics such as a Winston cone.

The rotatable mirror assembly **504** will now be described in detail.

Mirror assembly **41**, Figure **3**, includes a frame portion, an intermediate gimbals portion and an inner mirror portion preferably formed from one piece of crystal material such as silicon. The mirror portion may also advantageously be made of a suitable metal, such as Aluminum, stainless steel, Beryllium Copper. The silicon is etched to provide outer frame portion **43** forming an opening in which intermediate annular gimbals portion **45** is attached at opposing hinge locations **55** along first axis **31**. Inner, centrally disposed mirror portion **47**, having a mirror **29** centrally located thereon, is attached to gimbals portion **45** at hinge portions **55** on a second axis **35**, 90 degrees from the first axis. Mirror **29**, which is on the order of 100 microns in thickness, is suitably polished on its upper surface to provide a specular surface. In order to provide necessary flatness, the mirror is formed with a radius of curvature greater than approximately 2 meters, with increasing optical path lengths requiring increasing radius of curvature. The radius of curvature can be controlled by known stress control techniques such as, by polishing on both opposite faces and deposition techniques for stress controlled thin films, if desired, a coating of suitable material can be placed on the mirror portion to enhance its reflectivity for specific radiation wavelengths.

Mirror assembly **41** also comprises a first pair of permanent magnets **53** mounted on gimbals portion **45** along the second axis and a second pair of permanent magnets **53** is mounted on extensions **51**, which extend outwardly from mirror portion **47** along the first axis. In order to symmetrically distribute mass about the two axes of rotation to thereby minimize oscillation under shock and vibration, each permanent magnet **53** preferably comprises a set of an upper magnet **53a** mounted on the top surface of the mirror assembly **41** using conventional attachment techniques such as indium bonding, and an aligned lower magnet **53b** similarly attached to the lower surface of the mirror assembly as shown in Figures **3a - 3d**. The magnets of each set are arranged serially such as the north/south pole arrangement indicated in Fig **3c**. There are several possible arrangements of the four sets of magnets which may be used, such as all like poles up, or two sets of like poles up, two sets of like poles down; or three sets of like poles up, one set of like pole down, depending upon magnetic characteristics desired.

By mounting gimbals portion **45** to frame portion **43** by means of hinges **55**, motion of the gimbals portion **45** about the first axis **31** is provided and by mounting mirror portion **47** to gimbals portion **45** via hinges **55**, motion of the mirror portion relative to the gimbals portion is obtained about the second axis **35**, thereby allowing independent, selected movement of the mirror portion **47** along two different axes.

The middle or neutral position of mirror assembly **41** is shown in Fig, **3a**, which is a section taken through the assembly along line **3a-3a** of Figure 3. Rotation of mirror portion **47** about axis **35** independent of gimbals portion **45** and/or frame portion **43** is shown in Figure **3b** as indicated by the arrow. Figure **3c** shows the middle position of the mirror assembly **41**, similar to that shown in Figure **3a**, but taken along

line **3c-3c** of Figure **3**. Figure **3d** is a view similar to Figure **3c** but showing rotations of the gimbals portion of the mirror assembly. Rotation off the gimbals portion **45** and mirror portion **47** about axis **31** independent of frame portion **43** is shown in Figs. **3a - 3d** as indicated by the arrow. The above independent rotation of mirror **29** of mirror portion **47** about the two axes allows direction of optical beam **13** as needed by the optical switch units.

In order to protect hinges **55** from in-plane shock during handling and shipping, stops **57** are provided according to an optional feature of the invention as best shown in Figures **4** and **5**, which are enlarged sectional views taken on line **5-5** of Figure **3a**. At this point it should be noted that the mirror assembly is on the order of 100 microns thick, whereas hinge **55** of the same thickness is on the order of 10 microns wide, thereby providing robust strength in directions normal to the surface of the assembly. In order to provide protection against excess in-plane motion 90 degrees to the axis of the hinge, i.e., axis **31**, cooperating surfaces **61** on gimbals portion **45** and **63** on frame portion **43** are formed on either side of each hinge **55** and extend generally parallel to axis **31**. Surfaces **61** and **63** are spaced apart a selected distance such as 10 microns by way of example. In order to provide less in-plane motion. projection **65**, extending from surface **63** towards surface **61**, is formed to any selected distance such as 5 microns. It will be understood that such projection could be provided on surface **61** instead of **63** if desired. Similar stops are provided on the mirror and gimbals portions to provide protection against in-plane motion of hinges **55** relative to axis **35**.

According to another optional feature of the mirror, lock down tabs associated with each hinge are provided. As seen in Figure **6**, an example

showing one such hinge **55**, bridge portion **67** extends from gimbals portion **45** to frame portion **43** and locks the two portions together isolating hinge **55** from all normal manufacturing stresses. At the appropriate manufacturing step, the bridge portion **67** is cut providing gap **69** as shown in Figure **6a**: which allows normal rotation of gimbals portion **45** relative to frame portion **43** about the hinge **55**. This provides suitable stress protection for all hinges and significantly improves manufacturing yields.

With reference to Figure **3**, extensions **51** are preferably provided with laterally extending tabs **55a** which can be used to clamp down the mirror portion during assembly to thereby provide additional stress protection.

The movable mirror assembly **41** is received in a cavity **81a** of a header **81** which forms part of the mirror assembly package shown in Figures **7a-7d**. Header **81** is formed of any suitable material, such as ceramic in the case of a hermetic package and plastic where hermeticity is not required, and has a circumferentially extending shelf **81b** formed within cavity **81a** on which frame portion **43** of mirror assembly **41** is received. Bottom wall **81c** is spaced from shelf **81b** to provide clearance for movement of gimbals portion **45** and mirror portion **47**. Recesses **81d** are formed in bottom wall **81c** aligned with each set of magnets **53** to provide motion clearance for lower magnets **53b**. The size of the opening of recesses **81d** is maintained as small as possible, allowing suitable motion of the magnets, to facilitate making wall **81e** as thin as practicable, for example 125 microns. A window **83** allows the light beam to enter and exit the sealed package.

The magnet drive for the magnets comprise four air coils **91a-91d** (two shown in each of Figures **7c-7d**) each wound on a bobbin in turn

mounted on mounting bracket **85** and aligned with respective recesses **81d** and magnets **53**. The bobbin and bracket are made of suitable material for good heat transfer, magnetic dampening, and strength such as aluminum. The air coils are wound using high electrical conductivity materials such as copper. The bobbin has an air coil disposed proximate to top end **89a** of bobbin **89** such that the air coil is as close to magnets **53** as possible, for example, 200 microns, to provide full mirror rotation using minimum power.

An electrical wiring harness **87** is provided for required electrical connections to the micro-mirror assembly package **99** and comprises an elongated flex circuit **87** mounting a connector **95** at one end thereof for connection to a control system (indicated at **100**, Figure **7a**). An opening **87b** is formed at an opposite end which receives therein bobbins **89**. Coil leads **97** are attached to appropriate traces on the flex circuit as shown in **8a-8d**.

With particular reference to Figure **8**, micro-mirror assembly package **99** is precisely mounted and orientated in optical switch unit **15** utilizing cooperating registration surfaces of mounting bracket **85** and a portion of wall **16** of switch unit **15**. First opposing inclined surfaces **107** and **105** forming a somewhat convex configuration on mounting bracket **85** cooperate with respective second opposing inclined surfaces **103** and **101**, forming a somewhat concave, or cradle configuration, respectively, on bottom wall **16** of the switch unit. Mounting bolt **113** is received through bore **111** in bracket **85** and threaded bore **16a** in the cradle in bottom wall **16** to secure micro-mirror assembly package **99** within optical switch unit **15**. The cooperating opposed surfaces provide a precise registration in two planes while bolt **113** and its corresponding bore **111** in bracket **85** and threaded bore **16a** in wall **16** provides registration in a

third plane. It will be realized that the convex and concave configurations can be reversed if desired and further, that the surfaces can be fixed to one another by means other than a bolt. e.g., welding.

An alternate embodiment is shown in Figure 9 in which a single permanent magnet **54** is centrally located on the lower side of the mirror portion **47** in package **99A**. Air coils **89a-89d** are shown located in the same positions as in the Figures **3-7** embodiment and can be independently excited so that the interaction of the magnetic field of the permanent magnet and the coils cooperate to produce the appropriate magnetic field to cause movement of the mirror portion along each axis **31** and **35**, as desired. Although four air coils are shown, if desired, three air coils could be used to produce the desired magnetic field.

A micro-mirror assembly package made in accordance with the invention included a mirror portion which measured approximately 3 mm x 4 mm in width and length and had approximately 8 degrees of rotation about each of axes **31** and **35**.

Thus, described herein is a novel optical wireless modem capable of transmitting data of virtually any type across the ether via an optical link. The data that may be transmitted may be files and/or documents, voice, video, may be parallel or serial data, and may be analog or digital data. A wide variety of interfaces may be used to allow the modem to be used in conjunction with a wider variety of data media, such as LANs, device-to-device communications, Internet, etc. Encoding and decoding of various types may be employed, as well as any of a wide variety of error detection/correction. All of this is provided in a modem system that achieves very low cost, and is therefore available for use in a wide variety of applications, including those that an individual may have in his or her home. For example, a user may use an OWL according to the present invention to interconnect two or more personal computers, to provide a

home network. In addition, an OWL according to the present invention may be used by a data services provided to provide a link to a user's home, for example by employing a plurality of links on towers disbursed throughout a community. Thus, there are a great number and wide variety of applications for OWLs constructed in accordance with the principles of the present invention.

In using embodiments of the invention, the following method may be employed to establish and maintain an optical wireless communication link. The transmitter OWL is assumed to have a non-isotropic light source, such as a collimated laser, which can be modulated in some format with the transmitted data. The transmitter is also assumed to have a beam steering ability to direct the light in some range of directions (field of view) which is larger than the angular spread of the light source. It is also assumed that it is possible to roughly align the transmitter such that the receiver OWL lies within the field of view of the transmitter with a clear line of sight, and that at a given transmitter direction the receiver is able to detect the transmitted light. This is depicted in Figure 10, wherein it can be seen that a transmitter OWL 280 has a field of view 282. A receiver OWL 284 within that field of view 282 receives transmitted light 286.

In a first preferred method for using the present invention, it is also assumed that there is a secondary communication link 288 from the receiver OWL 284 to the transmitter OWL 280, as shown in Figure 10. This method is applied in an optical wireless communication link using half-duplex OWLs. Throughout this method the receiver OWL continuously monitors the intensity of detected light, and when the intensity of the detected light exceeds a threshold value corresponding to the value exceeding the random noise of the detector, a detector event is deemed to occur. The receiver records the time and intensity of the

detector light event as well as the data sent via the secondary communication link to the transmitter. In this method the following steps are performed:

1. The transmitter is approximately aligned to the receiver such that the receiver lies within the field of view of the transmitter.
2. The transmitter is initiated to begin transmitting a constant or varying optical signal and to scan the optical signal in an angular pattern such that when the scan is completed the transmitted light has crossed all positions in the transmitter field of view in time. Note that the spot has a spread. By providing a suitable pattern for the beam, the light can cover all points in the transmitter field during the scan. In the preferred embodiment the scan pattern is, basically, a spiral, that is, a series of expanding, or diminishing, circles or ellipses if the field of view is not symmetric. The spacing between the circles is chosen such that the angular area covered by the spot for two successive circles overlaps. To cover the complete field of view when it is not circular, e.g., when the field of view is rectangular, the scan pattern continues to expand the radius but is restricted to the field of view until the entire field of view is covered. For the case of a rectangular field of view, the ellipses are clipped on the sides so they remain in the field of view until the corners are covered by the scan pattern. After a signal is detected, the second, smaller scan pattern can be a spiral centered on the last detection event. The second method can use the same scan patterns as the first method. The pattern is correlated with time such that any moment in time during the scan corresponds to a determined angle. A flow chart for a preferred embodiment of the procedure by which the beam is controlled to scan in a circular spiral is shown in Figure 11. This is described in detail below.

3. As the transmitted light crosses the receiver photodetector a detector event occurs. The time and intensity for this event is recorded as data and that data is sent via the secondary communication link to the transmitter.
4. After receiving the time and intensity data, the transmitter correlates the time and intensity data and determines the predetermined position in which the receiver is located. The transmitter then begins a new scan centered on this position. The new scan area is smaller than the previous scan area.
5. When the transmitted light crosses the receiver area during the new scan such that the intensity of the detected light is greater than the previous detection event, the time and intensity of this new detected light event is recorded and data for this new event is sent via the secondary link to the transmitter.
6. If the intensity of light in the new detected light event is greater than the maximum intensity detection event during the last spiral, multiplied by a pre-determined factor greater than or equal to one, steps 4 and 5 are repeated, narrowing the search area in each repetition, until one of the following occurs:
 - a) The new scan generates no detection event with a detector intensity greater than the starting point of the scan. The transmitter returns to the center of the scan and verifies that the angle produces a continuous string of detection events with an intensity high enough for accurate data transmission. In this case, the center of the scan is the optimum angle for data transmission and the transmitter begins transmitting data. If this is not the case, the process returns to step 3 to re-scan the original scan area.
 - b) A sufficient number of repetitions occur such that the scan area is significantly smaller than the angular spread of the transmitter

light source, in which case the transmitter returns to the angle corresponding to the detection event during the last scan with the highest intensity and verifies that the angle produces a continuous string of detection events with an intensity high enough for accurate data transmission. In this case the center of the scan is the optimum angle for data transmission and the transmitter begins transmitting data. If this is not the case, the process returns to step 3 to re-scan the transmitter field of view.

The scan procedure of Figure 11 will now be described. In the discussion of Figure 11 the following variables are discussed, as set forth in Table 1.

Table 1

Variables used in Figure 11	
Variable	Definition
DetSig	Level of the signal from the detector
DSigMax	Maximum detected signal level
DSigMaxPosX	X point of the current maximum signal detected
DSigMaxPosY	Y point of the current maximum signal detected
NewSpiralCenterX	Current center of spiral in X direction
NewSPiralCenterY	Current center of spiral in Y direction
RefineLoops	Number of spiral refinement loops
SpiralRadius	Radius of current spiral pattern
Threshold	Signal trigger above noise level
Xpoint	Current X coordinate
Ypoint	Current Y coordinate

The scan begins **602** with the mirror set to direct the beam in the center of the scan area. The scan area is represented as a coordinate grid, having a horizontal axis, X, and a vertical axis, Y. Note that other representations are possible, and may be preferred, depending on the circumstances and preferences of the programmer; for example, an angle and radius coordinate system may be used. Xpoint, Ypoint and

RefineLoops are set to zero, while SpiralRadius is set to a previously stored parameter, Field of View, representing the field of view for the optical link **604**. The actual X and Y coordinates of the beam are determined from the PSD **234** (Figure 1), and stored as Xpoint and Ypoint, respectively **606**. The level DetSig of the signal from the detector is obtained **608**, and it is determined whether that signal level is greater than the current maximum, DSigMax **610**. If it is not, the procedure merely moves to the next point in the spiral, according to a simple algorithm defining the spiral shape **612**. However, if the detector signal level DetSig is greater than DSigMax then DSigMax is reset to DetSig, and the corresponding X and Y positions of the beam, Xpoint and Ypoint, respectively, are stored as the values DSigMaxPosX and DSigMaxPosY, respectively, **614**, thus setting the point of the current maximum signal. Note that the value DSigMax is preset with an initial stored value corresponding to a signal level above the noise, for example 3 to 10 dB above noise, as desired by the designer, as an initial value. Next in the procedure, it is determined whether DSigMax is greater than the predetermined threshold, Threshold **616**. If is not, then the procedure moves to the next point in the spiral **612**. However, if DSigMax is greater than Threshold, the following variables are reset: RefineLoops is set to RefineLoops+1, NewSpiralCenterX,Y are set to DSigMaxPosX,Y, respectively, Threshold is set to DSigMax(1+0.1) and SpiralRadius is set to $\frac{0.1 \cdot \text{SpiralRadius}}{\text{RefineLoop} + 1}$. This keeps track of the number of loops performed, readjusts the spiral center to the new center, increases the threshold by 10%, and decreases the spiral radius by a factor that increases with each loop and starts at 90%, thus causing the scan to "home in" on the right spot **618**. The procedure then returns to the measuring of the Xpoint and Ypoint values **606**. Returning to step **612**,

after the move to the next point in the spiral, it is determined whether the spiral is complete, based on the aforementioned spiral shape algorithm **620**. If it is not, the procedure goes to step **618**, and proceeds as described above. If the spiral is complete, however, it is determined whether the value RefineLoop is equal to zero **622**. If it is, that means the entire spiral has been completed without any signal being detected above the predetermined threshold. Therefore, the procedure stops **626**, since the receiver was not found in a complete scan. However, if RefineLoop is not zero, then that means that the receiver was found and that after some number of iterations no further increase in the detected signal level was achieved. Therefore, the procedure calls for holding **624**, since the receiver was found and the X and Y positions determined for best signal transmission.

An advantage of this method for establishing a link is that the receiver only has one task, that is, observing the signal intensity and relaying detector event data to the transmitter. All decisions are performed by the transmitter link control.

Note that in performing the method the laser output should be fairly constant relative to the time scale of the sweep pattern. This can be accomplished by either varying the data with an encoding scheme such as 4B/5B encoding which has equal numbers of 1's and 0's, on a short time scale, or by holding the laser signal constant. Both methods have a zero frequency (DC) component, but no low frequency variations, i.e., less than one MHz, for fast Ethernet with 4b/5b encoding.

Also note that the pattern need not be a spiral pattern. Any suitable search pattern may be used, such as a raster scan. Again, the beam has a spread, and it is desirable that whatever the pattern selected the pattern have overlaps such that the entire field of view is covered, once the scan is complete.

A second method for using embodiments of the invention will now be described. As in the first method, throughout this method the receiver continuously monitors the intensity of detected light, and when the intensity of the detected light exceeds a threshold value corresponding to the value exceeding the random noise of the detector, a detector event is deemed to occur. The receiver records the time and intensity of the detected light event as data, and this data corresponding to this event is sent via the secondary communication link to the transmitter.

1. The transmitter is approximately aligned to the receiver such that the receiver lies within the field of view of the transmitter.
2. The transmitter is initiated to begin transmitting a constant or varying optical signal and to scan the optical signal in an angular pattern such that when the scan is completed the transmitted light has crossed all positions in the transmitter field of view in time. The pattern is correlated with time such that any moment in time during the scan corresponds to a determined angle.
3. As the transmitted light crosses the receiver photodetector a detector event occurs. The time and intensity for this event is recorded as data and that data is sent via the secondary communication link to the transmitter.
4. The transmitter continues until the complete scan area has been scanned. A new scan area is chosen centered on the angle determined by the time corresponding to the highest intensity detector event during the previous scan. The new scan area is smaller than the previous scan area.
5. When the transmitted light crosses the receiver area during the new scan such that the intensity of the detected light is greater than the previous detection event, the time and intensity of the detected light

event is recorded and the data sent via the secondary communication link to the transmitter.

- 6) If the intensity of light in the new detected light event is greater than the maximum intensity detection event during the last spiral, multiplied by a predetermined factor greater than or equal to one, steps 4 and 5 are repeated, narrowing the search area in each repetition, until one of the following occurs:
 - a) The new scan generates no detection event with a detector intensity value greater than the starting point of the scan. The transmitter returns to the center of the scan and verifies that the angle produces a continuous string of detection events with an intensity value high enough for accurate data transmission. In this case the center of the scan is the optimum angle for data transmission and the transmitter begins transmitting data. If this is not the case, the process returns to step 3 to re-scan to original scan area.
 - b) A sufficient number of repetitions occur such that the scan area is significantly smaller than the angular spread of the transmitter light source, in which case the transmitter returns to the angle corresponding to the detection event during the last scan with the highest intensity and verifies that the angle produces a continuous string of detection events with an intensity high enough for accurate data transmission. In this case the center of the scan is the optimum angle for data transmission and the transmitter begins transmitting data. If this is not the case, the process returns to step 3 to re-scan the transmitter field of view.

An advantage of this second method for establishing a link is, as in the first method, that the receiver has only one task, that is, observing the signal intensity and relaying detector event data to the transmitter. All decisions are performed by the transmitter link control. An advantage

over the first method is that the threshold for detector events is not critical, since the entire field of view is scanned and the highest intensity detector event is chosen for the next scan. Therefore, spurious detector events unrelated to the transmitted light can be above the threshold, but if they are below the maximum intensity detector event, that will not affect the search process. In the case of the first method, described above, a spurious event will trigger a new scan area at an inappropriate angle. On the other hand, the advantage of the first method is that it is potentially a quicker method to perform, since the scans are terminated as soon as a detector event greater than the previous events occurs.

For a full-duplex optical wireless communications link with full-duplex OWLs on each side of the link, a two-way secondary channel is provided to transfer information between the OWLs. Each of the two transmitter-receiver combinations (transmitter from one OWL to the receiver in the other OWL) in the optical wireless link can be established independently using the steps described above for the half-duplex case.

A further embodiment **300** of the present invention is shown in Figure 12, and will now be described, for transmitting a composite analog video signal using a collimated light beam reflected off a beam steering micro-mirror. The source of the video signal is a composite video co-ax output of a DVD player **302**. The DVD video output is connected to an interface unit **304**, which includes two high speed op-amps **306**, **307**, for example THS4052 op-amps from Texas Instruments, Incorporated, for adjusting the DC offset and gain of the signal such that the voltage is always positive and is less than the maximum voltage for driving a laser diode. The video signal is provided to a first input of amplifying op-amp **307**, while op-amp **306** is connected to the second input of op-amp **307** and provides the offset to the output signal. The output of the interface unit **304** is connected to the transmitter section of an optical transceiver unit

308, which consists of a laser diode **309**, such as the VCT-F85A20 from Lasermate Corporation, mounted on a frame (not shown) such that the light beam **310** from diode **309** is directed to a lens **312**. The video signal is thus transformed from an electrical signal to a light signal.

The light output from the laser diode **309** is collimated using the lens **312**, which has the same optical characteristics of lenses used in laser pointers. The collimated light beam **314** reflects off a Silicon micro-mirror **316** in an optical module **318**, with the direction of the outgoing reflected light **319** being controlled by the angle of the micro-mirror **316**. The outgoing light **319** is partially reflected by a beam splitter **320**, such as a Melles Griot # 03BTF051, onto a PSD **322** for measuring the direction of the outgoing light. The micro-mirror orientation is controlled by a D/A unit **324**, such as a PA-DA12 board from Acqutek, in an IBM compatible computer **326**. The computer also contains an RF wireless RS232 unit **328**, such as a Unilink from Wireless Mountain, for communicating with a computer at the receiver.

A still further embodiment **400** of the present invention is shown in Figure **13**, and will now be described, for receiving a composite analog video signal. This is preferably the receiving portion of an optical transceiver in which the transmitting portion is as described in connection with Figure **12**. The light beam **402** to be received, for example a light beam like beam **319** from transmitter unit **300** (Figure **12**), is received by an optical module **404**, which consists of a lens **406** positioned to focus the light onto a 10mm PIN diode **410** of an optical transceiver **408**. The output of diode **410** is amplified in optical transceiver **408** by a pre-amplifier module **412**, such as a Thorlabs PDA155, the output of which is the output of the optical transceiver **408**. The output signal of the optical transceiver **408** is connected to a first input of a high speed op-amp **416** in

an interface unit **414**. Another high speed op-amp **418** is connected to a second input of op-amp **416**, and provides an offset to the output of op-amp **416**, which is the primary output **420** of optical transceiver **408**. The interface unit **414** thus offsets and amplifies the output signal of the optical transceiver **408** signal so it is compatible with a TV.

The interface unit **414** also includes a further high speed op-amp **422** having its input connected to the output of optical transceiver unit **408**. Op-amp **422** amplifies the signal and sends it to a A/D unit **424**, such as an Acqutek PA-AD12, in an IBM compatible computer **426**. The computer **426** also contains an RF wireless RS232 unit **428** to communicate via an RS232 line **430** with the computer on the transmitter side (not shown).

Assuming that a communications link is to be established using two optical wireless link transceiver units such as described above in connection with Figures **12** and **13**, a link is established by the transmitter computer **326** executing a first routine that causes the micro-mirror **316** to scan the light beam **319** in a spiral pattern of steadily increasing size, such that adjacent scans partially overlap, until an increase in the light signal is detected by the receiver computer **426**, which communicates that information through the wireless RS232 link **330/430** to the transmitter computer **324**. The transmitter computer **324** then executes a second routine that causes the micro-mirror to scan the light beam in a small search pattern around the angle at which the increase in light signal was detected, to find the optimum mirror orientation for peak signal transmission. This small search pattern can be an increasing spiral pattern, like the first pattern, but of smaller dimensions. The computer then holds the angles while the video signal is transmitted.

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims. For example, and not by limitation, systems may be put together including various of the elements described singularly herein, in order, for example, to make a network hub, or other arrangements of more complexity than the embodiments disclosed herein. In all such variations, the scope of the invention is to be delimited only by the appended claims.